

# A modelling analysis of the potential for soil carbon sequestration under short rotation coppice willow bioenergy plantations

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**Abstract.** Rising atmospheric CO<sub>2</sub> concentrations and their association with global climate change have led to several major international initiatives to reduce net CO<sub>2</sub> emissions, including the promotion of bioenergy crops such as short rotation coppice (SRC) willow. Although the above-ground harvested bio-fuel is likely to be the major contributor to the CO<sub>2</sub> mitigation potential of bioenergy crops, additional carbon may be sequestered through crop inputs into plantation soils.

Here, we describe a process-based model specifically designed to evaluate the potential for soil carbon sequestration in SRC willow plantations in the UK. According to the model predictions, we conclude that the potential for soil carbon sequestration in these plantations is comparable to, or even greater than, that of naturally regenerating woodland. Our preliminary, site-specific model output suggests that soil carbon sequestration may constitute about 5% of the overall carbon mitigation benefit arising from SRC plantations. Sensitivity analyses identified the following factors as the principal controls on rates and amounts of soil carbon sequestration under SRC: carbon inputs (net primary production), decomposition rates of the major soil carbon pools, initial soil carbon content (an inverse relationship with rates of soil carbon sequestration), crop/plantation management, and depth of soil being influenced by the bioenergy crop. Our results suggest that carbon sequestration potential is greatest in soils whose carbon content has been depleted to relatively low levels due to agricultural land use practices such as annual deep ploughing of agricultural soils.

**Keywords:** Organic carbon, soil, willows, short rotation forestry, models, UK

## INTRODUCTION

Following the United Nations Framework Convention on Climate Change Kyoto Protocol of 1997 (<http://www.cop3.de/>), the UK committed itself to a 12.5% reduction in CO<sub>2</sub> emissions from the 1990 baseline level during the first commitment period (2008–2012) (DETR 1998). This target corresponds to an average annual reduction in net CO<sub>2</sub> emissions of 19.6 Tg C (Tg=10<sup>12</sup> g) (Cannell *et al.* 1999). The Protocol promotes a range of strategies to reduce net CO<sub>2</sub> emissions, including increased energy use efficiency, greater use of non-fossil fuel energy sources, as well as demonstrable sequestration of atmospheric carbon through changes in land use/management.

In this paper, we focus on short rotation coppice (SRC) willow which has been identified as the 'bioenergy crop' with the greatest potential for carbon mitigation across the UK (Smith *et al.* 2000a,c). Willow is an ideal species for SRC in the UK because of its vigorous shoot regeneration

after coppicing, and its suitability to regional climate and soil conditions (Britt *et al.* 1995). Predicted yields range from 6–18 t DM (tonnes dry matter) ha<sup>-1</sup> yr<sup>-1</sup> (2.4–7.2 t C ha<sup>-1</sup> yr<sup>-1</sup>) (Armstrong 2000; Taylor & Bunn 2000; M. Dawson pers. comm.). Much of the carbon mitigation potential associated with the use of SRC willow as a bioenergy crop arises from its indefinite capacity as a 'carbon neutral' alternative to fossil fuel combustion. Nevertheless, the use of SRC bioenergy crops on previously agricultural soil could also lead to finite, but substantial increases in stored carbon pools below-ground (Smith *et al.* 2000a,c), due to increases in rootstock as well as enhanced soil organic matter carbon content. However, the mechanisms underlying any of these carbon storage processes in bioenergy plantations are little investigated, and not well understood. Indeed, it has recently been concluded that the principal uncertainties associated with bioenergy crops for carbon mitigation are those associated with soil carbon sequestration (Cannell *et al.* 1999; DETR 2000).

Two approaches have been used to investigate the potential for soil carbon sequestration under SRC bioenergy trees: field experimentation, and extrapolations based on data from

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regenerated woodland. One of the earliest experimental SRC trials contained poplar on previously tilled, agricultural prairie land in the USA (Hansen 1993). Initial establishment and tending of the plantations resulted in a net loss of soil carbon over the first 6–12 years compared to adjacent control grass and arable fields. However, over the full 18 years of the study, soil carbon to 1 m depth increased at an average rate of  $1.6 \text{ t ha}^{-1} \text{ yr}^{-1}$  compared to control fields. In a study of 7–8 year old poplar stands on grass and arable lands in Minnesota, no significant differences in soil carbon content between poplar and adjacent control fields were observed (Grigal & Berguson 1998). Similarly, a recent detailed analysis of data from a four year old willow plantation in the northeastern USA indicated no change in soil carbon pools compared to adjacent field controls (Uizen-Appiah *et al.* 2000). By contrast, substantial increases in soil carbon in the upper 10 cm layer of soil were observed after seven to nine years in a study of three mixed tree coppice plantation sites across Germany (Jug *et al.* 1999). However, the soil organic carbon content of deeper soil horizons (10–30 cm) at one of the sites was reduced by a similar rate, resulting in no net change in total soil carbon to 30 cm depth. In summary, the limited experimental data available so far indicate that there is substantial variability in the potential for soil carbon sequestration under SRC plantations because of within-site heterogeneities, as well as larger-scale variations in soil type, land-use history, climate, and crop productivity. Substantial further experimental research is required, as well as longer elapsed time since plantation establishment, in order to fully evaluate the timing and extent of soil carbon sequestration under bioenergy trees.

The principal UK and European spatial extrapolations and land-use comparisons of the  $\text{CO}_2$  emission mitigation potential of SRC (Smith *et al.* 2000a,b,c), have relied on soil organic carbon data from a single UK research site that has undergone natural woodland regeneration since 1883. By comparing the initial soil organic carbon contents (to 23 cm depth) at this site with those after 102 years, the average annual increase in soil carbon content was calculated as a percentage rate increase ( $1.17\% \text{ yr}^{-1}$ ). There are two major implications of this approach. Firstly, it assumes that the processes contributing to soil carbon sequestration under regularly coppiced and intensively managed plantations of monoculture bioenergy trees are analogous to those during natural woodland regeneration. Secondly, expressing the sequestration rate as a percentage of soil C implies that the higher the initial soil carbon content, the greater the potential sequestration rate. Clearly, these assumptions cannot be validated until long-term experimental data on soil carbon under coppiced bioenergy tree plantations become available. In the meantime, we propose a process-based modelling approach to predict potential C sequestration rates under SRC stands.

Here, we describe a simple, mechanistic model based on the classic carbon cycle modelling structure used in CENTURY (Parton *et al.* 1993) and RothC (Coleman & Jenkinson 1996). Simplification of this modelling structure in order to characterize soil carbon sequestration under coppiced willow was necessitated by the absence of sufficient parameterization data from bioenergy tree plantations. The

purpose of our SRC model is to provide a tool to investigate the main below-ground carbon flows in biomass energy crops, and the potential contributions that such crops might make to offsetting  $\text{CO}_2$  emissions over the duration of a series of crop harvests, and periodic plantation reestablishment events. To our knowledge, although several models have been developed to characterize SRC above-ground yields (Ceulemans *et al.* 1996; Isebrands *et al.* 1996), ours is the first process-based modelling approach specifically adapted to assess the potential for soil carbon sequestration in SRC plantations. Our objectives in this study were:

- (1) To develop a simple, mechanistic model that can accurately characterize recorded increases in soil carbon from a 100 yr old natural regeneration woodland site in the UK.
- (2) To estimate potential soil carbon sequestration rates in SRC willow plantations by parameterising the model with measured SRC production data.
- (3) To identify the major controls on soil carbon sequestration in SRC plantations through the use of model sensitivity analyses.

## METHODS

### *Modelling approach*

Our approach has been to develop a basic model that can predict the long-term record of changes in soil carbon (Poulton 1996) observed in a natural regeneration woodland site at the Geescroft Wilderness near Rothamsted (N  $51^\circ 48' 07''$ , W  $0^\circ 21' 41''$ ) in S. England. This site was under arable cropping for several centuries until the 1880s when it was fenced off and left unattended (Harmer *et al.* 2001). Initially, the area was colonised by damp-loving grass species, but by 1957 it had reverted to woodland, and most grassland species had disappeared. The site is now an oak-dominated deciduous woodland with sparse ground cover (Harmer *et al.* 2001; Poulton 1996). Soil samples taken in 1883, 1904, 1965, and 1985 indicate a steady linear increase in soil organic carbon in the 0–23 cm layer from  $28 \text{ t C ha}^{-1}$  initially, to over  $60 \text{ t C ha}^{-1}$  (a mean annual increase of  $0.33 \text{ t C ha}^{-1} \text{ yr}^{-1}$ ) (Poulton 1996).

Having calibrated our model according to the Geescroft dataset, key parameters specific to SRC such as tree production data and plantation management practices (harvesting and plantation reestablishment cycles of 3 and 24 years respectively) were applied in order to estimate plant and soil carbon pools expected in an SRC bioenergy plantation. The major assumption implicit in this approach is that soil processes are similar in the two systems. In other words, carbon inputs to the soil may differ, but once the carbon has entered the soil, the processes and rates of transformation are assumed to be similar in both SRC and naturally regenerated woodland systems.

### *Model development*

The model was developed on the basis of a simple mass balance of the major ecosystem pools and fluxes of carbon within a managed woodland or SRC plantation (Figure 1), and is adapted from the structure used by classic models of ecosystem carbon dynamics such as CENTURY (Parton

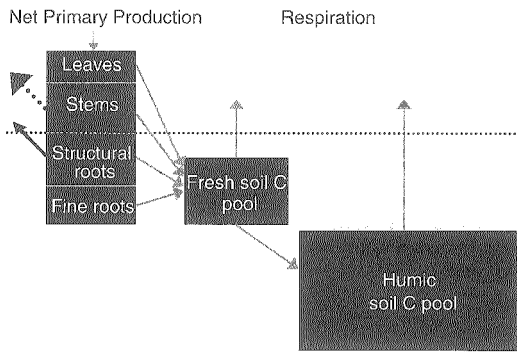


Figure 1. Schematic diagram showing the main carbon pools and fluxes used in the soil carbon sequestration model. The arrows on the left of the diagram indicate SRC carbon losses due to crop harvests (dotted line) and plantation reestablishment (solid line).

*et al.* 1993) and RothC (Coleman & Jenkinson 1996). For it to be appropriate for investigating changes in soil carbon over a century or so, the model runs on a yearly time-step. We characterized the major fluxes and pools (Figure 1) as follows:

**Biomass production.** Annual production was calculated using a version of Beer's Law:

$$dW/dt = Se_r(1 - e^{-kL})f_c \times 10 \quad (1)$$

where  $dW/dt$  is the growth rate of tree biomass (above- and below-ground) expressed in units of carbon ( $\text{kg C ha}^{-1} \text{yr}^{-1}$ ),  $S$  is the annual receipt of short-wave solar radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ ),  $e_r$  is the efficiency of conversion of this solar radiation into biomass ( $\text{g DM MJ}^{-1}$ ),  $k$  is the light extinction coefficient,  $L$  is the leaf area index ( $\text{m}^2 \text{leaf m}^{-2} \text{ground}$ ), and  $f_c$  is the fraction of carbon in the biomass ( $\text{g C (g DM)}^{-1}$ ). The factor of 10 is included to convert  $\text{g C m}^{-2}$  into  $\text{kg C ha}^{-1}$ . For both the woodland and SRC systems, values of  $k=0.6$ , and  $f_c=0.4 \text{ g C (g DM)}^{-1}$  were assumed. A preliminary study (Matthews *et al.* 1994) indicates that different tissue types vary slightly in carbon content: (e.g. fine roots and stem wood 0.38 and  $0.46 \text{ g C (g DM)}^{-1}$  respectively). For the sake of simplicity, and in the absence of sufficient data on the biomass and production of each component (as well as their carbon contents), we have used a single value for all tissue types throughout these analyses.

For the Geescroft Wilderness site, our model indicated that a value for  $e_r$  of  $0.21 \text{ g MJ}^{-1}$  gave the best fit to the observed production data (Jenkinson *et al.* 1992). This value represents an 'average' conversion efficiency and subsumes many different processes (e.g. vegetation succession, changes in tree density, growth rates, seasonal variation in carbon assimilation, etc.) over the 100 years under consideration.

Of the total net carbon assimilated each year, it is assumed that a fixed proportion ( $f_R$ ) is allocated to new root growth, with the remainder (i.e.  $1 - f_R$ ) allocated to above-ground growth. A value of 0.25 was assumed for  $f_R$ , which is within the range reported by Lambers *et al.* (1998). Using these values, and assuming a closed canopy and annual solar

radiation receipts of around  $4000 \text{ MJ m}^{-2} \text{yr}^{-1}$  (typical of values measured at Silsoe (N  $52^\circ 00' 19''$ , W  $0^\circ 25' 33''$ ) which is about 50 km from Geescroft), the model predicted an annual above-ground production from 10 years onwards of almost  $6300 \text{ kg DM ha}^{-1} \text{yr}^{-1}$ , corresponding to about  $2500 \text{ kg C ha}^{-1} \text{yr}^{-1}$ . Total net primary productivity (i.e. above- and below-ground growth) was predicted to be  $3350 \text{ kg C ha}^{-1} \text{yr}^{-1}$ , closely matching the value of  $3300 \text{ kg C ha}^{-1} \text{yr}^{-1}$  estimated recently for the site (Jenkinson *et al.* 1992).

For the short rotation coppice system, a value of  $e_r = 0.67 \text{ g MJ}^{-1}$  was chosen to match mean annual production data ( $14600 \text{ kg DM ha}^{-1} \text{yr}^{-1}$ ) measured on stands of short rotation coppiced willow in the UK (Armstrong 2000). This higher value of  $e_r$ , compared to the regenerated woodland system reflects not only the faster growth rates per tree of short rotation coppice, but also the higher planting densities associated with such systems.

**Leaf area index.** The maximum leaf area index ( $L$ ,  $\text{m}^2 \text{m}^{-2}$ ) achieved each year is one of the driving variables from which annual plant biomass production is calculated (see Equation 1), and is also used to calculate the amount of litter reaching the soil from the canopy (see Equation 2). As information is not available on the leaf area index in the Geescroft Wilderness dataset, we have assumed that it increased linearly up to a maximum value of  $9 \text{ m}^2 \text{m}^{-2}$  after 10 years, and remained at that value thereafter. A value of  $9 \text{ m}^2 \text{m}^{-2}$  is within the range of  $L$  values for temperate deciduous forests of  $3\text{--}12 \text{ m}^2 \text{m}^{-2}$  given by Larcher (1995), and is consistent with the leaf litter production data for the Geescroft Wilderness site measured by Poulton (1996), as discussed in the next section.

For the short rotation coppice system,  $L$  seems to be related to the age of the stand from time of planting (Persson & Lindroth 1994). Therefore, we have expressed  $L$  in the short rotation coppice system as a simple function of the age since plantation establishment, and in accordance with measured field data (Cannell *et al.* 1987), ( $L=2.3$  in the first year; 4.6 in the second year; and 7 in the third and subsequent years).

**Carbon inputs from canopy and root system.** It is assumed that all leaf material produced in a given year falls at the end of that year, and enters the 'fresh' soil carbon pool described in the next section. In addition, we have assumed that there is an age-dependent amount of wood detritus that falls to the ground and also enters the fresh carbon pool. This woody material includes not only branches and twigs that fall from the trees, but also trees that die due to self-thinning and other causes. The annual amount of carbon input into the 'fresh' soil carbon pool due to both of these canopy sources ( $W_{Cin}$ ,  $\text{kg C ha}^{-1}$ ) was calculated as:

$$W_{Cin} = \frac{L f_c}{SLA} \times 10^5 + W_{AC} f_W \quad (2)$$

where  $SLA$  is the specific leaf area (assumed to be  $250 \text{ cm}^2 \text{g}^{-1}$ ), and  $f_W$  is the fraction of the above-ground carbon input ( $W_{AC}$ ,  $\text{kg C ha}^{-1}$ ) that enters the fresh carbon

pool as woody material rather than leaf litter. This fraction was calculated as  $f_W = 0.015 / (1 + 100e^{-t})$  where  $t$  is the number of years since the start of the simulation in the case of the Geescroft Wilderness system, or since the last coppicing in the case of SRC. Thus, early in the life of the woodland or the coppicing cycle, almost all of the carbon input from the canopy is in the form of leaves, but as the stand grows older, progressively more woody biomass also enters the fresh carbon pool, up to a maximum of 1.5% per year of the above-ground biomass. In practice, in the short rotation coppice system, however, very little woody material actually enters the soil, as most is removed through harvesting before it becomes old enough to fall.

For the Geescroft Wilderness woodland after 100 years, the model predicted about 2300 kg C ha<sup>-1</sup> yr<sup>-1</sup> entering the fresh carbon pool from the canopy (i.e. leaf + woody material), of which 1440 kg C ha<sup>-1</sup> yr<sup>-1</sup> was from leaf drop. This leaf drop value is close to that measured by Poulton (1996) at Geescroft (1570 kg C ha<sup>-1</sup> yr<sup>-1</sup>).

It was assumed that a proportion ( $f_{FRTO}$ ) of the newly assimilated carbon allocated to the root system each year is lost as fine root turnover (i.e. root senescence) and enters the fresh carbon pool; this value also includes carbon lost from the roots through the processes of root respiration and rhizodeposition. In addition, we assumed that a fraction of the plant carbon below-ground also enters the fresh carbon pool through the death and decay of structural/woody root biomass. This fraction was assumed to be the same as that calculated for the above-ground woody detritus ( $f_W$ ). The total contribution of the carbon inputs into the 'fresh' carbon soil pool from the root system ( $W_{Rim}$ , kg C ha<sup>-1</sup>) were calculated as:

$$W_{Rim} = dW/dt f_{FRTO} + W_{BG} f_W \quad (3)$$

where  $W_{BG}$  is the weight of carbon below-ground in the root system (kg C ha<sup>-1</sup>). We assumed that half of the below-ground carbon in the root system is lost to fine root turnover on an annual basis ( $f_{FRTO} = 0.5$ ) in the Geescroft Wilderness site, but that this value was higher in the short rotation coppice system ( $f_{FRTO} = 0.85$ ) because of increased root senescence due to frequent coppicing above-ground.

In this way, the model predicted almost 750 kg C ha<sup>-1</sup> yr<sup>-1</sup> entering the fresh soil carbon pool from the root system in the Geescroft Wilderness woodland after 100 years, with total annual carbon inputs from both the canopy and the root system together being 3050 kg C ha<sup>-1</sup> yr<sup>-1</sup>. As a comparison, in the evaluation of a number of soil organic matter decomposition models on long-term datasets (Smith *et al.* 1997), the following values for carbon inputs into the system were used: RothC, 2850 kg C ha<sup>-1</sup> yr<sup>-1</sup> (Coleman *et al.* 1997); SOMM, 3140 kg C ha<sup>-1</sup> yr<sup>-1</sup> (Chertov *et al.* 1997); CANDY, 3000 kg C ha<sup>-1</sup> yr<sup>-1</sup> (Franko *et al.* 1997); NCSOIL, an initial value of 2160 kg C ha<sup>-1</sup> yr<sup>-1</sup>, then a value of 4396 kg C ha<sup>-1</sup> yr<sup>-1</sup> from 1957 onwards to simulate the conversion to full woodland (Molina *et al.* 1997); while the Verberne/MOTOR model (Whitmore *et al.* 1997) used a value of 3070 kg C ha<sup>-1</sup> yr<sup>-1</sup>.

*Decomposition of soil carbon pools.* For simplicity, it was assumed that there were two organic carbon pools in the soil, that of fresh carbon originating from recent tree growth, either from the canopy or from the root system (fresh organic matter: 'FOM'), and that of long-lived soil organic carbon (or humus: 'HUM'). As in most decomposition models (Paul & Clark 1996), decay of these two pools was assumed to follow first-order kinetics with different rate constants:

$$dC_p/dt = -C_p k_p \quad (4)$$

where  $dC_p/dt$  is the rate of change of the carbon pool  $p$  in question (kg C ha<sup>-1</sup> yr<sup>-1</sup>),  $C_p$  is the size of the pool (kg C ha<sup>-1</sup>), and  $k_p$  is the rate constant for each pool (yr<sup>-1</sup>). Each year, decomposition losses of carbon are subtracted from the pool in question, and any remaining carbon in the fresh organic pool is assumed to enter the humic carbon pool.

Preliminary simulations indicated that obtaining realistic rates of decay of the two soil carbon pools were critical to the development of an accurate model. To do this, we calibrated the model rate constants ( $k_{FOM}$  and  $k_{HUM}$ ) to the Geescroft Wilderness data. To facilitate the calibration procedure, we maintained a constant ratio between the two rates (on a daily basis) of 500:1 (i.e. decomposition of the fresh organic carbon pool was 500 times faster than the humic carbon pool), based on the approximate ratio of the corresponding rates used by the CENTURY model (Parton *et al.* 1994). In this way, calibrating the two rate constants to give the best fit to the Geescroft Wilderness soil carbon data produced values of 0.786 yr<sup>-1</sup> for  $k_{FOM}$  and 0.0031 yr<sup>-1</sup> for  $k_{HUM}$ , corresponding to turnover times of around 1.27 and 325 years, respectively. Expressed on a daily basis for comparison with other models, these values are 0.0042 d<sup>-1</sup> and  $8.5 \times 10^{-6}$  d<sup>-1</sup>. As a comparison, Parton *et al.* (1994) give values used in the CENTURY model of 0.01–0.05 d<sup>-1</sup> for surface and buried litter carbon, 0.00054 d<sup>-1</sup> for the slow soil carbon pool, and  $19 \times 10^{-6}$  d<sup>-1</sup> for the passive soil carbon pool. Molina *et al.* (1997) give calculated values for Pool III in the NCSOIL model (corresponding approximately to our humic carbon pool) ranging from  $7 \times 10^{-6}$  d<sup>-1</sup> to  $100 \times 10^{-6}$  d<sup>-1</sup>. It should be remembered in comparing these values that site differences in temperature, soil water status, and the C:N ratio of the organic material will all affect the actual rates of decomposition. Nevertheless, these studies indicate the values we have used for the two rate constants are within the range of previous estimates.

As a final approach to validation of our decomposition rates, we used the soil organic matter subroutine incorporated in the CERES family of crop models, and daily weather records from Silsoe to estimate mean decay rates of each soil carbon pool over a year. This submodel is based on the PAPERAN submodel described by Seligman & van Keulen (1981). As in our model, the CERES model assumes two soil carbon pools; one representing freshly added C, and the other a more stable humic pool. However, the fresh carbon pool is further divided into three sub-pools corresponding approximately to the carbohydrate, cellulose, and lignin fractions, each of which has a different potential

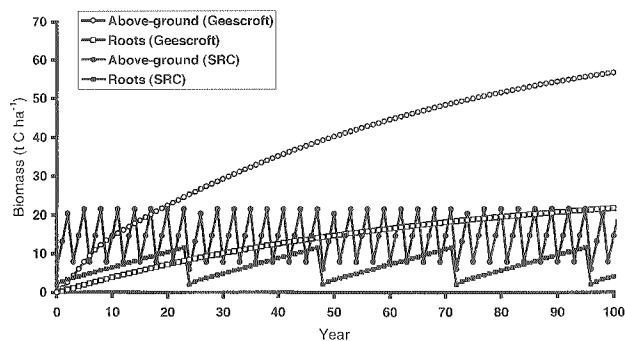


Figure 2. Predicted above- and below-ground biomasses for the Geescroft Wilderness woodland since regeneration, and for an SRC willow plantation system over 100 years. SRC harvest interval is 3 years, and total removal for replanting occurs every 24 years.

relative rate of decay (0.2, 0.05 and  $0.0095 \text{ d}^{-1}$  respectively under non-limiting conditions) (Seligman & van Keulen 1981). The potential maximum decay rate of the humic pool is  $85 \times 10^{-6} \text{ d}^{-1}$  in the model. However in practice, all of these potential relative rates of decay are usually reduced due to sub-optimal soil temperature and/or moisture conditions, as well as sub-optimal C:N ratios in the decaying material (Godwin & Jones 1991). We ran the CERES subroutine (with no crop present) using Silsoe daily weather data for 1991–1997 over an annual cycle to calculate actual rate constants for the fresh carbon and humic carbon pools that might realistically be expected at the nearby Geescroft site. The mean decay rate values obtained for the fresh carbon and humic carbon pools using the CERES model ( $0.0021 \text{ d}^{-1}$  and  $3 \times 10^{-6} \text{ d}^{-1}$  respectively), were about half of those obtained using the Geescroft Wilderness soil carbon data (see above).

**Tree harvesting.** In the SRC willow plantation scenario, harvesting at periodic intervals (3 years unless otherwise indicated) was simulated by removing all of the above-ground woody biomass from the system. Root material was assumed to remain in the soil at these harvests. Plantation reestablishment was simulated by removing all biomass, both above- and below-ground every 24 years.

**Soil carbon distribution.** In our model, we assumed that SRC plantations could influence carbon sequestration to a maximum soil depth of 0.5 m, and that 80% of the carbon in the humic pool occurs in the top 0.23 m soil layer to facilitate direct comparison with the Geescroft Wilderness data.

## RESULTS

### Model performance

**Biomass.** Our model indicated that above-ground and below-ground biomass in the naturally regenerated woodland scenario accumulate steadily, reaching about  $60 \text{ t C ha}^{-1}$  and  $20 \text{ t C ha}^{-1}$  respectively after 100 years (Figure 2). At the end of this period, annual wood increment was about  $0.2 \text{ t C ha}^{-1} \text{ yr}^{-1}$ . For the short rotation coppice plantation

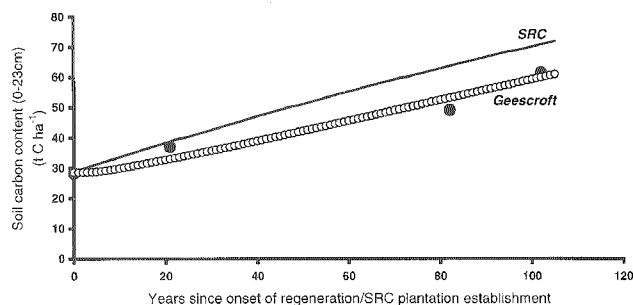


Figure 3. Predicted changes in soil carbon in the 0–23 cm layer for the Geescroft Wilderness woodland (open circles) and for a short rotation coppice plantation (solid line) growing on the same site. Measured data points (filled circles) for the Geescroft Wilderness site are also shown. SRC harvesting and replanting intervals as in Figure 2.

scenario, above-ground biomass is predicted to rise rapidly, reaching about  $20 \text{ t C ha}^{-1}$  within the third (i.e. harvest) year (Figure 2). This value corresponds to an average annual wood yield over the three year coppice cycle of about  $15 \text{ t DM ha}^{-1} \text{ yr}^{-1}$ , which is typical of many SRC willow stands in the UK (Armstrong 2000). By contrast, below-ground biomass is predicted to increase steadily up to about  $12 \text{ t C ha}^{-1}$  at the time of plantation reestablishment (Figure 2).

**Soil carbon.** Our model predicted a slightly higher rate of soil carbon sequestration in the SRC system as compared to that of the Geescroft Wilderness natural regeneration woodland (Figure 3). This prediction assumes similar soil type, initial soil carbon content, soil drainage characteristics and climate for each scenario. The average rate of carbon sequestration in the soil to a depth of 23 cm in the Geescroft Wilderness scenario was  $0.31 \text{ t C ha}^{-1} \text{ yr}^{-1}$ , while that in the SRC scenario was  $0.41 \text{ t C ha}^{-1} \text{ yr}^{-1}$ . These values correspond to soil carbon sequestration rates to 50 cm depth of  $0.40 \text{ t C ha}^{-1} \text{ yr}^{-1}$  and  $0.51 \text{ t C ha}^{-1} \text{ yr}^{-1}$  respectively.

### Sensitivity analyses

We used the model to identify the parameters to which soil carbon sequestration rates under SRC plantations were most sensitive by varying the value of each major parameter, while holding all the others constant. For these analyses, we assumed a harvesting interval of three years, complete removal for replanting every 24 years, and that the plantation was grown on the same soil, and in the same climatic conditions as at the Geescroft Wilderness site. For each simulation, we ran the model for 100 years, and used the annual rate of soil carbon sequestration averaged over the 100 years as the indicator variable to evaluate the sensitivity. Parameters were categorized into those that influenced the rate of carbon input into the soil system, and those that influenced the rate of loss of carbon from the soil system. We look at each of these in turn.

**Annual above-ground wood production.** The rate of above-ground wood production (i.e. harvested wood yield) was

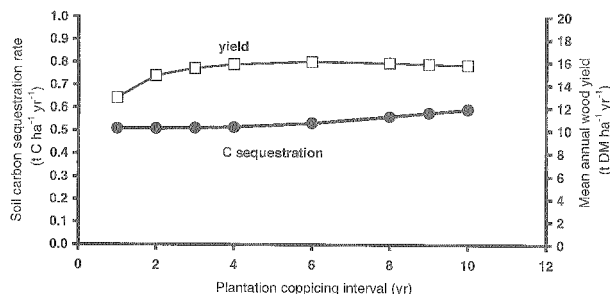


Figure 4. Predicted relationship between mean annual soil carbon sequestration rate (to 50 cm depth) and harvesting interval (filled circles) for a short rotation coppice plantation. Corresponding mean annual wood yields (dry matter) are also shown (open squares).

varied by changing the solar radiation conversion efficiency ( $e_r$ ) between  $0.2\text{--}1.6\text{ MJ m}^{-2}\text{ d}^{-1}$  to encompass the full potential range in yield values for short rotation coppice plantations in the UK ( $2\text{--}42\text{ t DM ha}^{-1}\text{ yr}^{-1}$ ) (I. Tubby Forest Research pers. comm.). As a result of the associated changes in leaf and wood litter production above- and below-ground, carbon inputs to the soil altered, leading to average soil carbon sequestration rates ranging from about  $0.2\text{ t C ha}^{-1}\text{ yr}^{-1}$  to  $1.1\text{ t C ha}^{-1}\text{ yr}^{-1}$ . This linear relationship {Sequestration ( $\text{t C ha}^{-1}\text{ yr}^{-1}$ ) =  $0.021 \times \text{yield}$  ( $\text{t DM ha}^{-1}$ ) +  $0.19$ } indicates that about  $21\text{ kg C}$  accumulates in the soil for every  $1\text{ t}$  of wood dry matter yield under these environmental conditions and harvesting regime. Therefore, these figures suggest that the carbon sequestered annually in the soil of a short rotation coppice plantation at this locality would represent about  $5.3\%$  of the carbon accumulated annually as renewable bioenergy fuel.

**Total below-ground carbon inputs.** From a mechanistic perspective, it is the flow of carbon to below-ground from leaf, stem and root detritus that directly enhances soil carbon sequestration. Total below-ground carbon input was varied from  $1.7\text{--}6.4\text{ t C ha}^{-1}\text{ yr}^{-1}$  (by altering  $e_r$ ) in order to directly calculate the relationship between carbon input and soil carbon sequestration rates {Sequestration ( $\text{t C ha}^{-1}\text{ yr}^{-1}$ ) =  $0.18 \times \text{carbon input}$  ( $\text{t DM ha}^{-1}$ ) -  $0.09$ }. The slope of the relationship indicates that about  $18\%$  of the total carbon entering the soil contributes to the increase each year, most of the rest returning to the atmosphere as  $\text{CO}_2$  from microbial respiration.

**Harvesting interval.** The model predicted that altering the interval between coppice harvests from 1–10 years slightly increases the rate of soil carbon sequestration (Figure 4). As the interval lengthens, the increase in soil carbon sequestration is largely caused by higher soil carbon inputs due to an increasing amount of woody litter production from both above- and below-ground as the stand ages. For the same reason, average wood yield declines slightly after about 3–6 years (Figure 4), as an increasing amount of woody material is lost from the canopy. Average annual wood yields are substantially diminished at coppicing intervals of less than 3 years (Figure 4).

**Decomposition rates of soil carbon pools.** In all our analyses, we have assumed a constant ratio between the rates of decay of

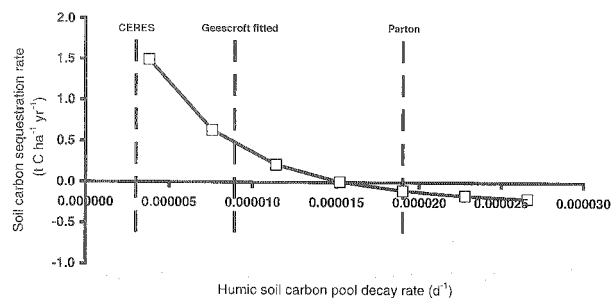


Figure 5. Relationship between mean soil carbon sequestration rate (to 50 cm depth) and decomposition rate of the humic carbon pool in a short rotation coppice system. The decomposition rate of the fresh carbon pool is assumed to be 500 times faster (on a daily basis) than that of the humic carbon pool in each case. For comparison, the humic pool decomposition rate obtained by fitting the model to the Geescroft Wilderness soil data is shown, as are the values given by Parton for a tropical ecosystem (1994), and those calculated by the CERES model using UK climate data (see Methods).

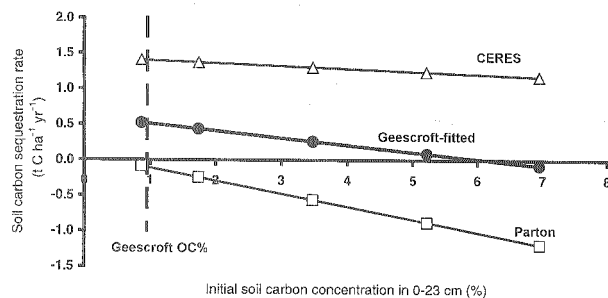


Figure 6. Relationship between mean soil carbon sequestration rate (to 50 cm depth) and initial soil organic carbon concentration in the 0–23 cm layer in a short rotation coppice system using decomposition rates obtained by fitting to the Geescroft Wilderness data (filled circles). Also shown are the corresponding relationships for decomposition rates given by Parton (1994) (open squares) and calculated by the CERES model using UK climate data (open triangles). The initial soil organic carbon concentration at the onset of woodland regeneration in the Geescroft Wilderness site in 1883 is shown for comparison.

the fresh and humic soil carbon pools (see Methods). Thus, as expected, the soil carbon sequestration rate was very sensitive to the rate of decomposition of the humic carbon pool, particularly below values of about  $15 \times 10^{-6}\text{ d}^{-1}$  (Figure 5). At decomposition rates higher than this value, the model suggests that a net loss of soil carbon would occur in this particular system (Figure 5). Clearly, there is much uncertainty in the estimation of humic pool decomposition rates that are appropriate for local soil moisture and temperature conditions, and different soil organic matter C:N ratios. The values that we calculated for our model are about midway between the climatically adjusted CERES estimate (see Methods), and the Parton *et al.* (1994) value for tropical ecosystems, indicating that the humic pool decomposition rate used here is well within range of more established and developed estimates.

**Initial soil carbon content.** The initial carbon content of the soil into which short rotation crops are established is important in determining potential rates of soil carbon sequestration because rates of carbon loss from the humic

